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To cite this version:

Shenle Pan, Damien Trentesaux, Duncan Mcfarlane, Benoit Montreuil, Eric Ballot, et al.. Digital interoperability in logistics and supply chain management: state-of-the-art and research avenues towards Physical Internet. Computers in Industry, 2021, 128, pp.103435. 10.1016/j.compind.2021.103435 . hal-03161524

HAL Id: hal-03161524
https://hal.science/hal-03161524v1

Submitted on 10 Mar 2023

Version of Record: https://www.sciencedirect.com/science/article/pii/S0166361521000427
Manuscript_e3dcab414d5bdfe3775fd3a7a4c72788

Digital Interoperability in Logistics and Supply Chain Management: State-of-the-art and research avenues towards Physical Internet

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Abstract: Interoperability is playing an increasing role for today's logistics and supply chain management (LSCM) because of the trends of cooperation or coopetition. Especially, digital interoperability concerning data or information exchange becomes a key enabler for the next evolutions that will massively rely upon digitalization, artificial intelligence, and autonomous systems. The notion of Physical Internet (PI) is one such evolution, an innovative worldwide logistic paradigm aimed at interconnecting and coordinating logistics networks for efficiency and sustainability. This paper investigates how digital interoperability can help interconnect logistics and supply networks as well as the operational solutions for sustainable development, and examines the new challenges and research opportunities for digital interoperability under the PI paradigm. To this end, we study the most relevant technologies for digital interoperability in LSCM, via a bibliometric analysis based on 208 papers published during 2010-2020. The results reveal that the present state-of-the-art solutions of digital interoperability are not fully aligned with PI requirements and show new challenges, research gaps and opportunities that need further discussion. Accordingly, several research avenues are suggested to advance research and applications in this area, and to achieve interconnection in logistics and supply networks for sustainability.

Keywords: Interoperability, Interconnection, Physical Internet, Digitalization, Logistics, Supply Chain Management, Bibliometric review, State-of-the-art, Research avenues

1. Introduction

Subject to the trends of economic globalization and offshoring production, today's logistics and supply networks are more complex and stringent than ever before (Ivanov and Dolgui, 2020a). As a result, the challenges facing logistics and supply chain management (LSCM) are also much higher, as it should support operations that must be more efficient, effective, agile, resilient, and sustainable. One of the most obvious consequences is that today's supply networks are more and more interdependent and interconnected for the purpose of collaboration, including vertical cooperation and horizontal coopetition (Pan et al., 2019a). Such interdependence and interconnection should strongly rely on quick and efficient information communications. However, disruptions, such as Fukushima disaster in 2011 or the COVID-19 outbreak, have obviously exposed the vulnerability of the contemporary global supply chains, that is mainly due to the lack of end-to-end supply chain visibility, and information traceability and transparency (Ivanov and Dolgui, 2020a). These problems are essentially related to the issue of interoperability.

In the context of LSCM, interoperability refers to the ability of independent logistics and supply networks to mutually conduct operations and business with one another, in order to use the functionality of other networks, or to execute operations for others (based on (Barthe-Delanoë et al., 2014; Chen et al., 2008; Leal et al., 2019)). Generally speaking, interoperability should be considered at physical level (e.g., standardized handling), organizational level (e.g., inter-organizational protocols) and business level (e.g., business models with shared value), and digital level (Pan et al., 2019b).

The contemporary LSCM lays particular stress on enhancing digital interoperability. One main reason is the paradigm shift towards digital and data-driven transformation in logistics systems and services (Hofmann and Rüsch, 2017). Since LSCM involves a large number of companies and stakeholders often from multi-industry and multi-area, how they can efficiency and effectively communicate with each other is a critical issue to deal with. The digital transformation has yielded digital solutions and tools to achieve this end; but they are often performed by one single service provider at operational level. As a result, these solutions are not necessarily interconnected and this mostly leads to information silos (contrary to other solutions like EPCglobal). This has given rise to the need of enhancement of digital interoperability in LSCM.

For the purpose of consistency, this paper defines digital interoperability as (synonymous with *digital connectivity* in this paper): *the ability to achieve quick, seamless, secure, and reliable data and information exchange between computing devices (viz. devices being able to transfer data), between information systems (of organizations, infrastructures, logistics networks), or between devices and systems, for the aim of enhancing cooperation or coopetition of independent logistics parties or networks*. Even though some researchers suggest *interoperability* referring to *digital interoperability* exclusively (such as Leal et al. (2019)), this paper uses the term digital interoperability to avoid any ambiguity. Besides, different to the recent review of (digital) interoperability assessment in (Leal et al., 2019), our work focuses on digital interoperability in LSCM, and considers distinct research questions and keywords.

Especially, this work investigates the digital interoperability issue under a specific logistics paradigm, namely *Physical Internet* (PI) which is one of the emerging breakthrough paradigms aimed at achieving global seamless interconnection of logistics networks. As a physical metaphor of the digital internet, PI advocates the interconnection and openness of independent logistics and/or supply networks for some important advantages (Montreuil, 2011; Ballot et al., 2014). For example, PI could help achieve the synergies expected among service providers via sharing logistics assets or schemes, resulting in around 17% fill rate increased in transportation means and 60% CO_2 emissions saved from freight transportation (Sarraj et al., 2014). Moreover, PI advocates standard-based open logistics networks which would encourage *plug & play* solution providers and the interconnection to enhance logistic flexibility, agility, and resilience. For example, Yang et al. (2017a) show that, facing with disruptions, distributed and interconnected inventory services could help reduce up to 35% total logistics costs (including transportation, inventory holding and shortage). The business collaboration enabled by PI and based on distributed operations could also promote the co-creation of value in supply chain, especially for sustainability by digitalization (Sallez et al., 2016).

In this paper, we pay special attention to the questions of how digital interoperability can help interconnect logistics and supply networks as well as the operational solutions for sustainable development, and what are the new challenges and research approaches towards the PI paradigm. The methodology used in this work is summarized in Figure 1. After defining the research problem and questions, the next step is to analyze the state-of-the-art via a bibliometric literature review. This statistical method can help us identify and track the critical topics and trends in related literature. Based on the results, and the expert analysis on the new challenges of digital interoperability in PI, a new framework is developed to categorize the identified solutions and topics. This step can help further identify research gaps and new opportunities. Then, interdisciplinary approaches and solutions are investigated to suggest new research avenues to advance the research and application of digital interoperability in the PI area. This work tackles the problem from interdisciplinary perspectives since LSCM is in essence a field of interdisciplinary research. In addition to the well-known approaches and methods from Operations Management/Operations Research (OM/OR), other disciplines such as Robotics, Computer Science or Data Science have been increasingly involved as key drivers and enablers in digitalizing and optimizing logistics and supply chain operations. These disciplines put forward the issue of digital interoperability (e.g. connection of information systems, data, or objects), meanwhile providing new solutions to the same objective (see discussion in Section 5). The most promising emerging technologies, techniques, breakthrough concepts and paradigms from both researchers and practitioners are of particular interest to investigate.

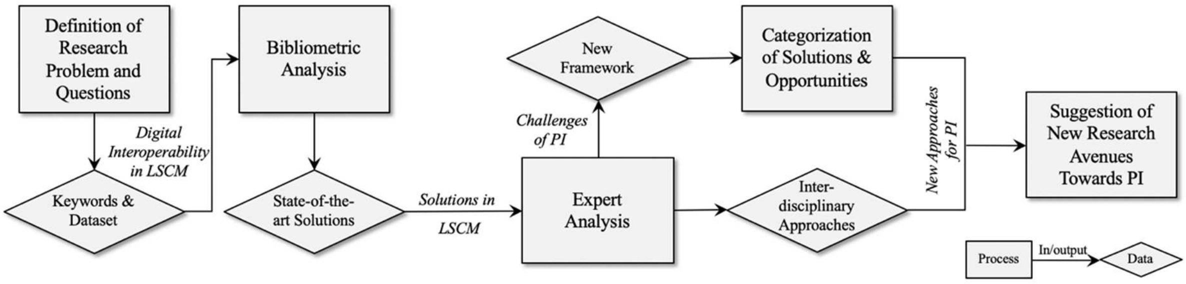

Figure 1. Methodology Flowchart

This paper is organized as follows. Section 2 introduces the paradigm of PI and discusses the key role of digital interoperability under the paradigm. The European PI implementation roadmap (ALICE, 2020) is also outlined. Section 3 focuses on a bibliometric analysis of the state-of-the-art of digital interoperability. Section 4 then presents a cross-analysis of the new PI challenges and the results of this state-of-the-art analysis. Section 5 discusses new avenues and approaches to advance the research and applications of digital interoperability towards PI. Finally, Section 6 concludes the work.

2. Digital Interoperability: a key enabler for Physical Internet

2.1 Physical Internet for logistics sustainability

Physical Internet (PI) was originally defined by Montreuil (2011) as "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols". Evolutive variants of this definition are provided in (Ballot et al., 2014; Pan et al., 2017a). The concept has rapidly developed and evolved in recent years, thanks to the development-research synergies among researchers and practitioners. For the state-of-the-art, readers may refer to several recent survey papers, e.g., Henrik and Andreas (2017), Ambra et al., (2018) and Pan et al., (2019). Recently, Crainic and Montreuil (2016) and Oger et al., (2018) suggested to extend PI from interconnectivity to hyperconnectivity of logistics and supply chains, in which a system is said to be hyperconnected when its components and actors are intensely interconnected on multiple layers, ultimately anytime, anywhere. Notably, hyperconnected logistics system relies upon interconnectivity layers including digital, physical, operational, transactional, legal and personal layers, aiming at manipulating these layers as a whole to improve logistics capability, efficiency and sustainability.

As of today, the development and deployment of PI is underway around the world. Two principal approaches to achieve PI can be observed. On the one hand, the top-down approach that addresses the PI system from holistic perspectives, also called holistic approach. Within this approach, PI-related research is broken down into sub-areas and problems that eventually belong to different disciplines providing scientific support, for example, the axes in the PI roadmap in Figure 3, or the sub-areas outlined in (Treiblmaier et al., 2020). On the other hand, the bottom-up approach starting from parts of PI systems, i.e., reductionist approach. This approach is particularly important as more and more service innovations in industrial development and applications are inspired by, or aligned with the PI paradigm, e.g., *Mixmove* or *CRC Services* for interconnected transportation services, *FLEXE* or *Stockbooking* for interconnected inventory services. The practitioners as well as academia who are interested in the PI concept raise the question of how to integrate, or generalize these innovative services into PI system to achieve full interconnection or hyperconnection of all parts. The question conduces to rich opportunities of practice-based research for academia or company's R&D. The development-research synergies create a virtuous cycle that is advancing the development and deployment of PI.

More importantly, along its development PI has been perceived as a worldwide logistics paradigm shift towards efficiency and thus sustainability. The European Technology Platform *ALICE* adopted PI as a major avenue with decarbonization towards achieving zero mission logistics in Europe by 2050 (ALICE, 2019). It is foreseeable that PI as a key enabler will revolutionize the current logistics paradigms in order to cope with the sustainable issues. As discussed below, the revolution is to be achieved through interconnected organizations, new organizational models, and digitalization.

From collaboration to interconnection: PI will strengthen logistics services available to partners and competitors. As aforementioned, PI aims at interconnecting supply and logistics networks in a multi-industry context. To this end, interoperability being an ability residing in the networks at physical, digital, business and organizational level plays essential role. Such an interoperability will further enhance and foster both vertical cooperation of buyer-supplier dyad on a single chain and horizontal cooperation among competitors at the same level across supply chains. Especially, the latter is also called logistics *coopetition* (Plasch et al., 2020). Resources and information sharing for logistics synergies are examples of the foreseeable advantages of the interoperability, which have already been demonstrated by a number of academic studies and research projects (see the survey in (Pan et al. 2017a)). Recent researches also showed that both vertical and horizontal cooperation could make use of PI for collaborative planning; and the cooperation could be coordinated via a neutral entity that orchestrates the resources (Plasch et al., 2020), or via rule-based incentive mechanisms which are more applicable for decentralized coopetition between service providers (Lafkihi et al., 2020). Furthermore, interoperability will also encourage cooperation and synergy at product design or manufacturing level, for example in favor of circular economy and industrial symbiosis (Herczeg et al., 2018). Promising perspectives should be further investigated.

Evolution of organizational models: PI may provide opportunities to shift the logistics organization from dedicated or integrated to interconnected or federated models. The literature shows that logistics collaboration has been dominated by centralized organizational models, in which a party will play the role of central authority of organization, coordination and optimization for the others. Examples include supply chain integration, Vendor-Managed Inventory (VMI), collaborative planning, and logistics pooling (Cruijssen et al., 2007; Kadiyala et al., 2019). These organizational models have achieved some success in a single SC or small-scale collaborations, but they are now being challenged in the supply networks that are much more complex and often large-scale. As a result, interconnected and decentralized models are attracting growing attention (Treiblmaier et al., 2020). Decentralization relies on collaborative rules, protocols and incentive mechanisms that all parties agree upon, and subject to which they can make own decisions for self-interest, rather than only following instructions from central authority. Different examples of decentralization can be found in logistics planning, for example in transport planning (Gansterer and Hartl, 2018; Lafkihi et al., 2020), inventory management (Yang et al., 2017b), or real-time transit routing via PI-crossdocking centers (Chargui et al., 2020). Recently, Handfield and Linton (2017) have introduced Federated Supply Chain Networks (FSCN) as an organizational model. They suggest that parties in FSCN operate in a decentralized way, but they are aligned based on a strong, dominant central firm and guided by a common centralized purpose imposed by the firm. More generally speaking, it can be argued that the central role can also be played by a variety of entities, such as an authority that could be a supervisory board or a coalition, a virtual algorithm-based decision-making procedure, or even vote-based consensus protocols.

Digitalization: PI will accelerate the digitalization of LSCM and *vice versa*. According to its goals and framework, PI will put forward dynamic, intelligent and real-time decision making at the logistics level (Ballot et al., 2014). Digitalization and data-driven models across logistics and supply networks are essential prerequisites to support this type of decision-making. PI can play a dual role to this end. On the one hand, PI can provide a framework for use cases or testbeds of practical environment for implementing the most advanced technologies and techniques from other disciplines like computer science or data science. Recent example of PI-based use cases include intelligent PI-containers (Sallez et al., 2016), machine learning for collaborative transport planning (Vanvuchelen et al., 2020), Cyber Physical Systems (CPS) for PI-based city logistics (Kong et al., 2020). On the other hand, PI may serve as a practical paradigm for digital supply chain design, as it puts special emphasis on reaching system modularization, standardization, and interoperability at digital level. Hence, PI can be seen as a key trigger for digitalizing supply chains and logistics.

2.2 The key role of digital interoperability in PI

There is a rich existing literature relating to enterprise and network interoperability, for example, see the enterprise architectures in (Chen et al., 2008). In this section, the well-known 5C model developed by Lee et al. (2015) is adopted to discuss the key role of digital interoperability in PI, because the model is in accord with PI's scope and ambition. More specifically, the 5C model is an architectural model aiming to guide implementation of CPS in smart manufacturing, under the Industry 4.0 paradigm. As shown in Figure 2, the model describes the functions and attributes at five levels, of which smart connection is the most basic, but essential level for the higher levels of intelligence. Even though the term digital interoperability was not explicit in the paper, and the interconnectivity issue was mostly discussed at Machine-to-Machine (M2M) level, the model clearly shows the critical role of digital interoperability in smart/autonomous systems, especially in light of the *plug & play* attribute.

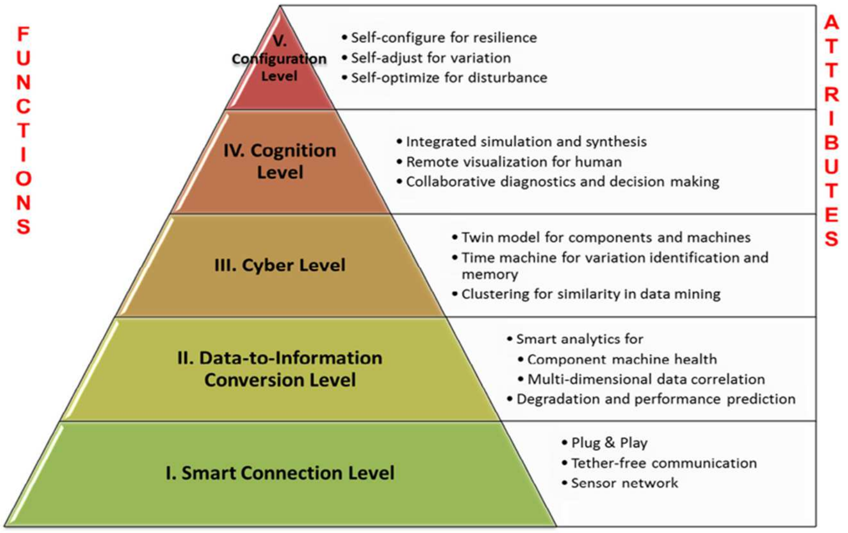

Figure 2. 5C architecture for implementation of Cyber-Physical System from Lee et al. (2015)

The challenges of digital interoperability are even more evident and complex at supply network level than at manufacturing level, since the former involves often an international multi-system, multi-party, multi-network context. As shown Figure 3, the co-creation of a so-called *System of Logistics Networks* is one of the major axes for realizing PI, in which interconnectivity (notably including physical, business, and digital level) is a key step. It is expected to achieve vertical and horizontal network interconnectivity by 2030 in Europe, which is also an essential prerequisite for fully autonomous PI network by 2040. Digital interoperability is one of the major millstones to achieve these goals. For details, readers may refer to the roadmap presented in (ALICE 2020).

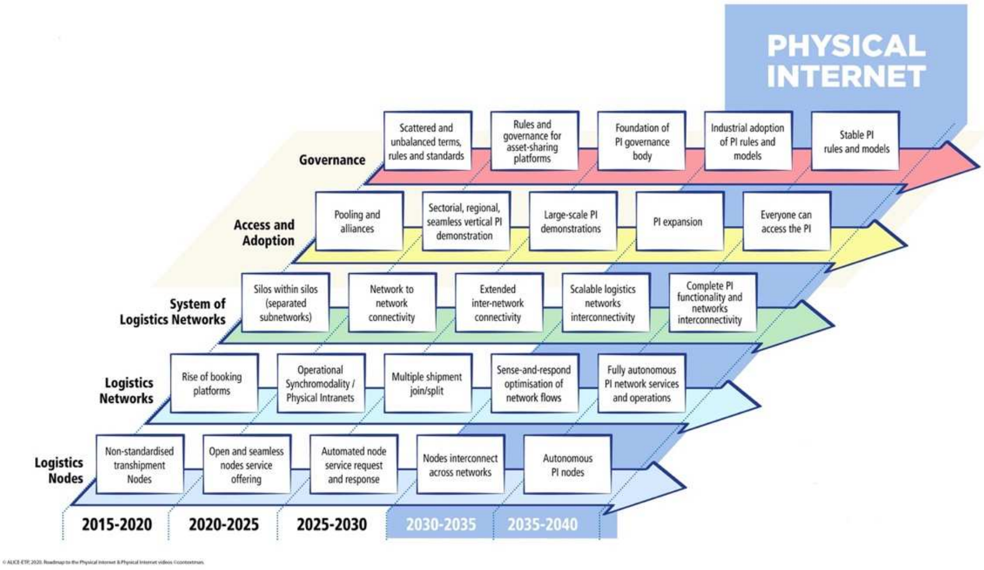

Figure 3 : The Physical Internet Roadmap (version 2020 from ALICE (2020), www.etp-logistics.eu)

Several key roles of digital interoperability in PI can be discussed. First, digital interoperability is required to ensure *quick, reliable, secure, and seamless sharing of data or* *information* among different systems, among companies, or among networks. This objective has two major perspectives: strengthen collaboration among companies (business-to-business communications), and support automated and autonomous logistics systems (M2M communications). Effective and efficient Information and Communications Technologies (ICT) are particularly of interest to this end. Examples include Industrial Internet of Things (IIoT), digital platforms and cloud like the industrial data space, Application Programming Interface (API), low-power wide-area network like Lora, Narrow Band Internet of Things (NB-IOT), or 5G (see a benchmark study of wireless technologies in (Garcia et al. 2018)).

Second, *privacy preservation* is an important attribute expected in digital interoperability. The attribute is particularly critical in logistic collaboration through PI, which involves multi-parties that could be direct competitors, i.e. coopetition. It is certain that digital interoperability for information sharing helps in collaboration that aims to improve logistics efficiency. However, for incentive compatibility, individual information privacy should be protected during the collaboration. But it sometimes comes with a price to efficiency, in other word, the tradeoffs between privacy and efficiency. Recent literature shows already great interest in investigating the issue with different approaches, for example, Mechanism Design (Sui and Boutilier, 2011), data techniques such as data mining or machine learning (Aggarwal and Yu, 2004), or other technology-based approaches such as Blockchain.

Third, *trackable and traceable sharing* of data is another desirable objective of digital interoperability. As aforementioned, nowadays supply and logistics networks are complex and interdependent. Data error might be spread, or amplified easily through the network, e.g., the well-known Bullwhip effect. Tracking down errors and responsibility is therefore becoming necessary in the cases of, for example, data missing, product recall, and product conservation problems. To this end, using a single central data platform to store historical data for traceability is an unlikely option for large supply or logistics networks like those supported by PI. Communications or distributed data storage techniques show their potential to tackle this issue, e.g., blockchain, embedded intelligence, or could or edge computing (Zhong et al., 2016).

3. The state-of-the-art: bibliometric analysis

To track the current critical topics and trends in the literature relating to digital interoperability in LSCM, the methodology of bibliometric analysis is adopted for statistical analysis of such trends, which is well established in the literature (Leal et al., 2019; Dolgui et al., 2020). The methodology in this work consists of four steps: 1) define research questions; 2) data collection; 3) descriptive analysis; (4) categorization analysis and reporting results. The software *VOSviewer* is used for results visualization, which is commonly used in the literature (van Eck and Waltman, 2014).

3.1 Research questions and keywords

The main research questions for the review are: (RQ1) how can digital interoperability help interconnect logistics and supply networks for sustainable development; (RQ2) what are the new challenges and research approaches under the PI paradigm? More specifically, the following sub research questions are studied:

> (SQ1) what are the main research foci of the last decade literature related to digital interoperability in LSCM?
>
> (SQ2) what statistical information can be learned from the bibliometric analysis (the most influential researchers and the co-authorships, keyword and occurrence, etc.)?
>
> (SQ3) what are the new challenges and promising topics strongly relevant to PI?

Based on these questions, the following keywords are firstly considered for queries: "*interoperability*" *OR* "*digital connectivity*" *AND* "*supply chain*" *OR* "*logistics*". The first two terms enable all related literature to be covered according to Leal et al. (2019). The second two terms of "supply chain" and "logistics" will be adequate to cover the field (see Step 2 in Table 1).

3.2 Data collection

We follow the paper selection methodology suggested by Durach et al. (2017). Table 1 presents the three-step methodology, with the inclusion and exclusion criteria.

Step 1 – Criteria for inclusion	**Reasoning**
Paper published from 2010 to October 2020 (as of the date of this work)	Up-to-date studies published over the past decade
Source type of peer-reviewed academic journals and conference proceedings	To focus on high quality transdisciplinary publications
Paper written in English	English is the dominant language in SC and logistics research
Paper investigating interoperability in SC and logistics	This is the research problem of this work
Step 2 – Data search	
This step is concerned with two tasks. • The first task is to select data sources. *Scopus* is used as the main source since the database	

covers most of the peer-reviewed academic journals, especially in engineering field (Pirola et al., 2020). • The second task is to define the list of keywords and construct database queries. We first queried the combination of “interoperability” OR “digital connectivity” AND “physical internet” in article title and keywords. Only few papers were found. It is then necessary to extend the scope by replacing “physical internet” by “supply chain” or “logistics”. Combining with the criterions in previous step, the query string in Scopus is as follows: *(TITLE("interoperability" or “digital connectivity” and "supply chain" or "logistics") OR KEY("interoperability" or “digital connectivity” and "supply chain" or "logistics")) AND PUBYEAR > 2009 AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (SRCTYPE,"p") OR LIMIT-TO (SRCTYPE,"j")).*
Step 3 – Paper selection
A total of 261 papers were identified after step 2. Then, the irrelevant or double papers were removed, based on the sources, information from title and abstract. Most of the removed papers concern technical standards or reports, or other fields of media, medicine and healthcare, or energy that are not related to SCM. Finally, 208 papers are selected in the bibliometric analysis.

Table 1. Three step paper selection methodology (adopted from Durach et al. (2017))

3.3 Descriptive analysis

Using software to conduct bibliometric statistics and visualize results is a common approach in the literature (van Eck and Waltman, 2014). In this work, *VOSviewer* is selected to analyze the dataset of 208 papers identified above and visualize the results. The software uses the association strength to calculate similarity of two items, and their own techniques for clustering, mapping and viewing. More technical information can be found in (van Eck and Waltman 2014). Note that, in the software setting, full counting in the statistics and association normalization for result visualization are selected. Other settings are by default.

In regard to Sub question (SQ2), special attention has been paid to several analyses, i.e., authors, sources, documents per year, most frequent keyworks. Especially, some abbreviated, overlapped or interchangeable terms are unified for statistic purpose, e.g., supply chains to supply chain, semantic interoperability/web to semantics, radio frequency identification to RFID.

3.3.1 Co-authorship analysis

The first analysis is to identify the most influential authors and groups in the dataset. 631 authors have been identified from the 208 documents. After applying a filter of minimum 2 documents and 1 citation, 62 authors are selected; and the co-authorship links are displayed in Figure 4. Five important clusters can be observed, which are Grilo (green), Jardim-Gocalves (blue), Panetto (pink), Bicocchi (purple), and Wang & Wong (orange). The clusters Jardim-Gocalves and Panetto are weakly connected. The top 10 productive and most-cited authors out of the 62 are listed in Table 2. Note that some authors receive the same number of citations because of co-authorships, i.e., Irizarry and Karan, Trajanović and Zdravković, or Beulens and Verdouw. The figure and table indicate that the most influential researchers are, Grilo, Jardim-goncalves, Espadinha-cruz, and Panetto. The information given by the figure and table could help readers (especially young scholars) identify the most influential researchers and their works in an efficient manner.

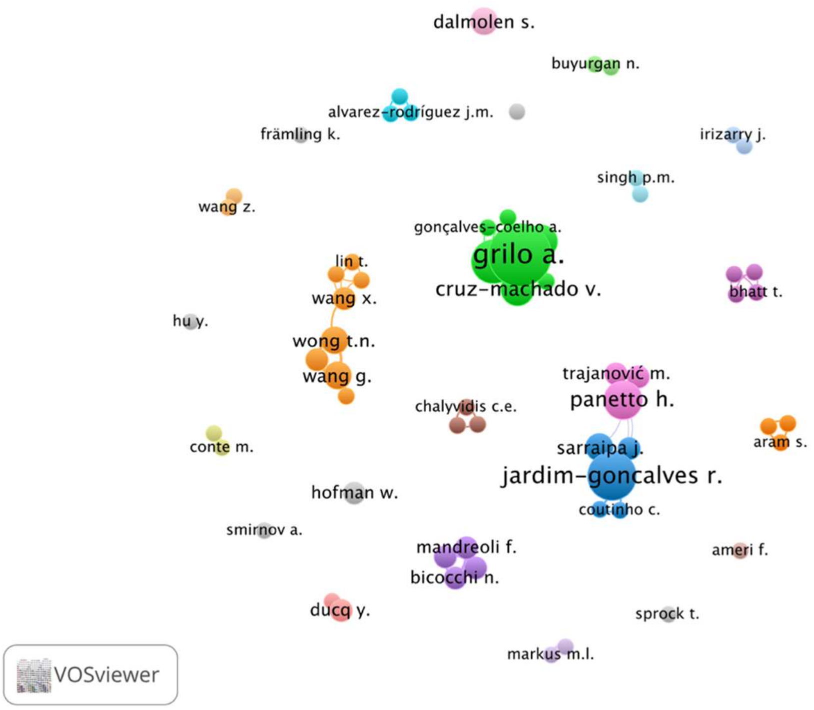

Figure 4. Network visualization of co-authors analysis based on the identified papers (62 authors with at least 2 documents and 1 citation, weighted by documents)

Author	Documents	Author	Citations
Grilo a.	11	Irizarry j.	203
Jardim-goncalves r.	8	Karan e.p.	203
Espadinha-cruz p.	7	Jalaei f.	192
Panetto h.	6	Panetto h.	176
Cabral i.	5	Jardim-goncalves r.	111
Cruz-machado v.	5	Trajanović m.	93
Dalmolen s.	4	Zdravković m.	93
Sarraipa j.	4	Främling k.	87
Wang g.	4	Beulens a.j.m.	86
Wong t.n.	4	Verdouw c.n.	86

Table 2. Top 10 productive and most-cited authors among the identified papers

3.3.2 Documents per year and sources

Figure 5 illustrates the distribution of documents from 2010 to October 2020 (as of the date of this work). The number of publications per year varies from 11 to 28. Regarding sources, 150 sources were found from the dataset, including conference proceedings and journals. *The*

International Journal of Computer Integrated Manufacturing is the source with the most publications of 8 documents, while *Automation in Construction* is the most cited source (355), *Computers in Industry* in second place in terms of publications or citations. Table 3 exhibits the top 10 cited journals of the dataset, with the number of publications. Note that the sources are ranked by citations because of the approximate number of documents. The results could help readers efficiently identify the most important and influential journals related to the research problem.

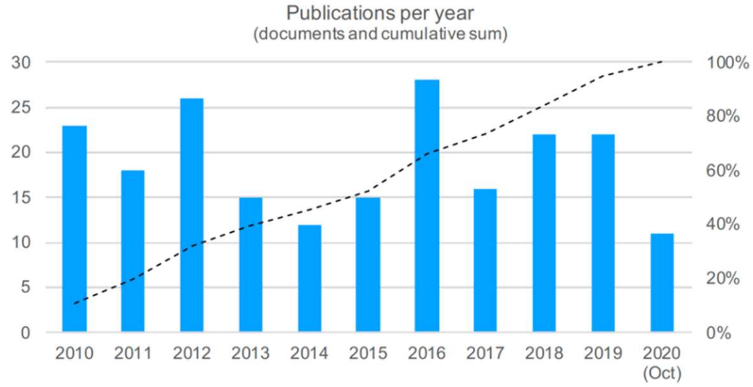

Figure 5. Number of publications per year among the identified papers (as of October 2020)

Sources	Citations	Documents
Automation in construction	355	4
Computers in industry	244	7
International journal of computer integrated manufacturing	92	8
IEEE World forum on IoT 2016	85	2
Expert systems with applications	79	2
Journal of intelligent manufacturing	62	2
Procedia computer science	54	3
Simulation	40	2
International journal of production research	39	3
Journal of cleaner production	36	3

Table 3. Top 10 cited journals among the identified papers

3.3.3 Keyword occurrence analysis

In order to perceive the research foci in the past decade, we analyze the most frequently used keywords via the co-occurrence analysis in *VOSviewer*. Table 4 exhibits the top 75 (with minimum 5 occurrences in the dataset) out of 2062 keywords in total. Removing first two terms “interoperability” and “supply chain” that are the keywords of the query, the top 10 technical terms are: semantics, ontology, information management, information systems, information services, service oriented architecture (SOA), web service, decision making, life cycle, IoT. Further, the keywords are grouped into five clusters as displayed in the table (by the best-performance resolution setting in *Vosviewer* after running different configurations). It can be observed that: Cluster (1) of 16 keywords mainly concerning information sharing, communication; Cluster (2) of 16 keywords mainly related to design, life cycle, and sustainability; Cluster (3) of 15 keywords mainly concerning data format, handling and storage; Cluster (4) of 15 keywords mainly related to collaboration and competition in interoperable business and SC; Cluster (5) of 13 keywords mainly concerning the technologies of semantic web and virtual agents. Although the categorization of several terms in the table could be discussed, the clustering step clearly outlined the main research streams among the identified papers.

Complementarily, Figure 6 visualizes the co-occurrence and yearly overlay of the keywords. In the figure, the size and the color of a circle respectively refers to the importance (occurrence) of the keyword and the publication year. For example, it is clear that ontology and semantics are the two keywords of importance that follow interoperability and supply chain (the keywords of the query). On the other hand, the terms colored yellow and light green represent the keywords frequently occurred during the last two year that can be considered as emerging research foci, e.g., information use, blockchain, network architecture, big data, industry 4.0, internet of things. Moreover, the figure also shows the strength of keyword relation in accordance with the clustering above, i.e., strongly related keywords are closely located together. For example, it can be observed that interoperability is strongly related to supply chain and to manufacture. Likewise, ontology and semantics are closely related. Contrarily, the outermost points are relatively weakly related to the other keywords, i.e., weak co-occurrence. The information can help identify the most recent and related topics for the research of interoperability in LSCM.

Cluster (1)			**Cluster (2)**			**Cluster (3)**			**Cluster (4)**			**Cluster (5)**		
Keyword	**Occ.**	**TLS**	**Keyword**	**Occ.**	**TLS**	**Keyword**	**Occ.**	**TLS**	**Keyword**	**Occ.**	**TLS**	**Keyword**	**Occ.**	**TLS**
information systems	24	163	decision making	17	108	information management	25	164	interoperability	182	802	semantics	45	270
information services	22	140	life cycle	17	104	internet of things	15	90	supply chain	156	762	ontology	35	219
soa	20	117	logistics	17	68	information use	14	106	manufacture	30	167	multi agent systems	12	73
web service	18	111	electronic data interchange	13	71	rfid	12	69	industry	14	72	data integration	8	55
integration	10	75	product design	12	62	blockchain	8	26	competition	13	80	virtual corporation	8	54
business process management	9	71	architectural design	11	64	industry 4.0	8	37	standards	12	61	virtual enterprise	8	54
design	9	64	bim	11	69	data handling	7	51	enterprise interoperability	11	53	intelligent agents	7	52
information dissemination	8	53	enterprise resource planning	9	52	network architecture	7	47	business interoperability	10	46	supply chain network	7	39
information sharing	8	57	sustainable development	8	50	big data	6	42	collaboration	10	62	cloud computing	5	31
information technology	8	48	project management	7	45	embedded systems	6	41	commerce	10	51	decision support systems	5	42
knowledge management	6	44	environmental impact	6	37	traceability	6	33	automotive industry	7	37	intelligent systems	5	24
system interoperability	6	36	automation	5	41	cost effectiveness	5	29	ecosystems	7	27	knowledge representation	5	35
electronic commerce	5	29	construction industry	5	24	digital storage	5	32	industrial management	6	21	semantic technologies	5	28
enterprise resource	5	48	information and	5	25	industrial	5	46	global supply	5	29			

management			communication technologies			research			chain					
enterprise system	5	38	information theory	5	35	legacy systems	5	28	sales	5	20			
information retrieval	5	47	sustainability	5	27									

Table 4. Clusters and occurrence of the frequent keywords among the identified papers (minimum 5 occurrences; Occ.= occurrences; TLS= total link strength computed by *VOSviewer*)

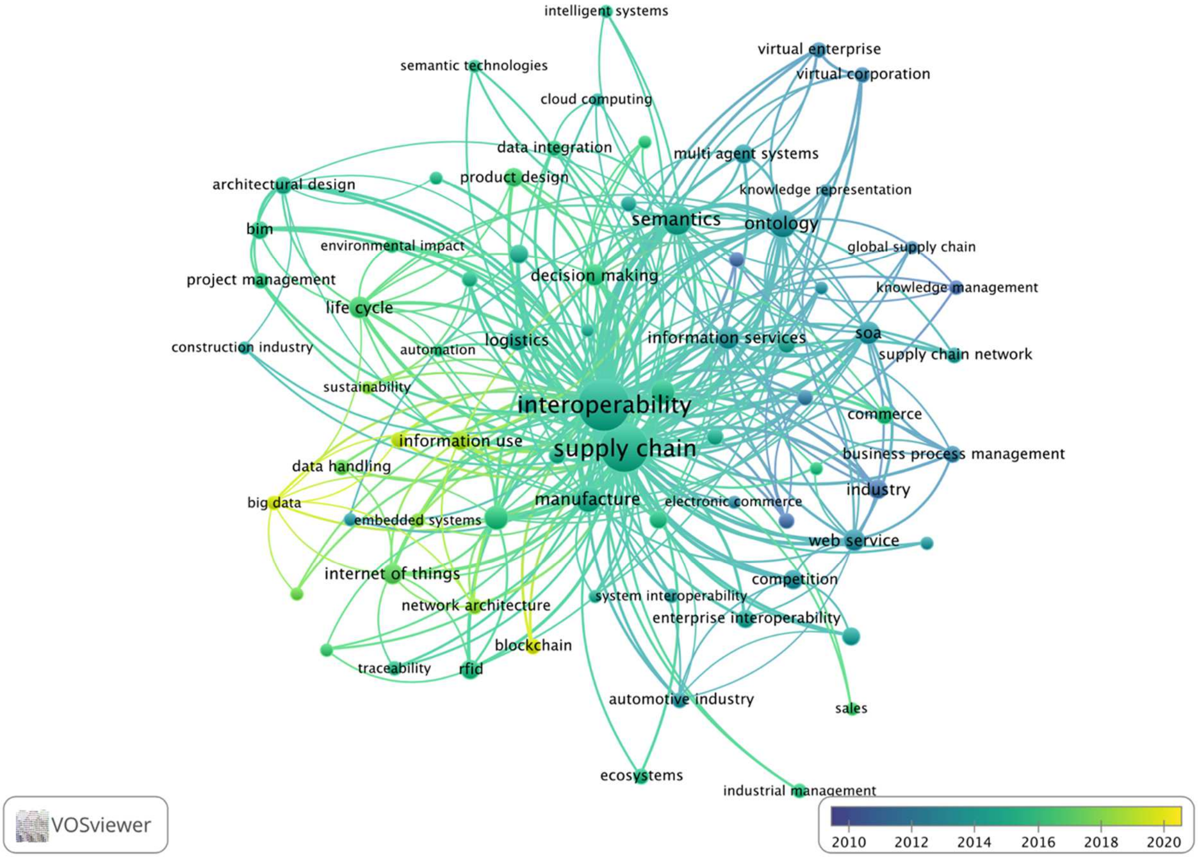

Figure 6. Overlay visualization of co-occurrence of keywords among the identified papers (minimum 5 occurrences, weighted by occurrences)

The bibliometric analysis above has pictured the state-of-the-art solutions for digital interoperability in LSCM. The keyword clustering helps find out the main research streams from the identified papers in the past decade. It is clear that PI was not among the critical topics, since it is relatively new to the related literature. How the solutions align with PI need further investigation. The next section will address the last sub question (SQ3) about the new challenges and promising topics relevant to PI, which is also the last step in the methodology of categorization analysis and reporting results.

4. Challenges for digital interoperability from PI

The bibliometric review shows that a number of solutions for digital interoperability exist in the literature, including theoretical research and real-life applications. Meanwhile, the PI paradigm will put forward some new challenges to the current state-of-the-art of digital interoperability. There appears to be a lack of structural classification of the solutions in face of the new challenges. Following the methodology in Figure 1, this section aims to first discuss several new challenges from PI, then use them to classify the solutions from the analyzed literature. More specifically, based on the author's expertise in LSCM and especially PI, we focus on four challenges that are the most classical, important and frequently studied in the literature related to ICT (cf. challenge 1 and 2 below) and LSCM (cf. challenges 3 and 4 below). The most representative keywords from Table 4 translating the main research foci in the past decade, will be re-categorized into each challenge (see Table 5), in order to identify the research opportunities and gaps.

Challenge 1: **Effective and open inter-organizational data sharing format**. This challenge mainly concerns the question about how information is structured, formatted, arranged, configured, queried in order that multiple organizations can make use of what they are permitted to access. Since PI is defined as an open logistics system, that is especially attractive for *plug & play* service provides as well as other parties. Data standard is especially important in such context. However, it is more and more difficult to apply one single standard for all parties, except for the GS1 standards. New standardization technologies to format and structure data are getting growing attention, such as ontology, semantics, EDI (Electronic Data Interchange) (Anand et al., 2012; Grubic and Fan, 2010; Hakimi et al., 2011).

Challenge 2: **Effective and open inter-organizational communications**. This challenge deals with the question of how the information can be securely and effectively transferred between organizations. Traditional communication ways in logistics (such as e-mails, calls, worksheets) seem inadequate to support quick, reliable, secure, and seamless sharing of data (or information) as required for PI. More efficient and effective communication channels or intermediaries must be developed and employed for PI. Some new technical or technique solutions have been being proposed and investigated, see the contributing technologies most studied in the literature in Table 5. The widespread contributing technologies are, for example, Service oriented Architecture (SOA) or semantic and web service, mostly applied in SC integration and business process management (Garcia-de-Prado et al., 2017; Huang and Lin, 2010).

Challenge 3: **Privacy, security, or access restrictions**. This challenge addresses the issues of privacy and security of data, i.e., what is the data content that could be shared and how secure the sharing is. Due to the effect of competitive intelligence (Panetto et al., 2016), companies are more and more cautious about sharing data. In collaborative or coopetitive practices, most of logistics parties are reluctant to share their data (or are not allowing direct access), despite of the mutual value that can be gained from it. That is why privacy-preserving solutions have been developed and getting increasing attention. For example, cloud-based orchestration for access restrictions in which data is shared via cloud services, and user's access right is defined by a widespread agreement among all users (collaborators). Other disruptive solutions include anonymous data exchange via blockchain, and privacy-preserving machine learning methods, that will be discussed later.

Challenge 4: **Product-oriented and order-oriented data**. This challenge is concerned with the generation, collection and valuation of data in exchange process. In other words, it should be figured out what data is needed and why. Data can be collected from the objects (assets, products, etc.), or from business process (orders, sales, etc.). For the former, IoT technologies are massively used, and commonly applied in product design and life cycle such as intelligent product (Barbosa et al., 2016). For the latter, data-driven decision making techniques are often employed to take advantage of the (shared) data in logistics operations, for example, intelligent logistics involving customer data (McFarlane et al., 2016), or distribution optimization considering real-time demand information (Shi et al., 2020).

Challenges	**Short description**	**Contributing technologies (keywords from the literature)**
1-Data sharing format	Content format or structure	semantics, ontology, standards, RFID, EDI, knowledge management
2-Communications	Channel or intermediary for exchange	information services, enterprise information systems, SOA, business process management, integration, web service, cloud computing
3- Privacy & security	Restrictions and security	information management, information use, big data, blockchain, data handling, digital storage, ecosystems
4-Product/order-oriented data	Collection and valuation	treatability, product design, life cycle, IoT, embedded systems, BIM, decision making, sales,

Table 5. Key contributing technologies to the challenges (excerpted from Table 4)

Based on the bibliometric analysis, some research gaps and opportunities can be further identified. Although the literature has so far paid adequate attention to the four major challenges of digital interoperability in PI, the present state-of-the-art solutions are not fully aligned with PI requirements that are discussed in Section 2.2, e.g., seamless data sharing of data, privacy preservation, trackable and traceable data sharing. To overcome the gap, recent interdisciplinary innovative and disruptive technologies should gain more attention. For example, it is surprising to notice in Table 4 the absence of some recent key approaches or technologies, such as Machine Learning, Smart contracts, Digital twin, autonomous systems. That might be due to two reasons: on the one hand, they could be considered weakly relevant to interoperability, or not specially in LSCM field; on the other hand, they were still in the infancy in the period reviewed. In the next section, we discuss more comprehensively these approaches and solutions as well as the gaps and opportunities under the suggested research approaches towards PI.

5. New research avenues and approaches towards PI

To tackle the four introduced challenges of digital interoperability in PI, four avenues and approaches are suggested for future research, which cover highly promising innovative solutions and concepts from interdisciplinary perspectives. They are: 1) Coopetitive, federated logistics networks; 2) Autonomous and self-organizing logistics systems; 3) Digital Twins in Logistics and Supply Chain; and 4) Smart infrastructures and communities. Table 6 explains how these avenues link to the challenges introduced in Section 4 with the key contributing technologies and concepts. It is worth noting that these technologies or concepts could be applied to different challenges or approaches; and they are designated according to the most prominent contribution.

Future approaches	**New challenges of PI**			
	Data sharing format	Communications	Privacy & security	Product/order-oriented data
Coopetitive, federated networks	*Data standards*	*API* *data platform* *graph database*	*federated learning* *differential privacy*	*big data* *reinforcement learning* *control tower*
Autonomous and self-organizing systems	*IoT standards* *Web of things* *semantics* *ontology*	*M2M communications* *smart contract* *ICT (5G, LoRa....)*	*blockchain*	*intelligent product* *ITS* *embedded systems*
Digital Twins in logistics and supply chain		*cloud computing*	*sensors & cloud security*	*life cycle* *BIM*
Smart infrastructures and communities		*data marketplace*	*ecosystems*	*context awareness* *smart city*

Table 6. Suggested research approaches and key contributing technologies and concepts

We now discuss each of these proposed avenues in detail.

5.1 Coopetitive, federated logistics networks

Due to the strong (either horizontal or vertical) competition in logistics and SC, we suggest that coopetitive, federated models are more adequate for open SC collaboration as well as digital interoperability. As depicted in Section 2, coopetitive, federated logistics networks can be seen as logistics systems in which all parties cooperate in a decentralized way, being aligned based on common goals and consensual frameworks which are agreed upon or set by a central authority managing the system. PI could be a practical example of such network. This new organizational model should strongly rely on digital interoperability as well as the solutions, especially with respect to data privacy preservation.

Among the promising technologies or concepts listed in Table 6, it is highly likely that machine learning, federated (machine) learning in particular, will become an important research avenue especially for decision optimization with respect to data privacy. Different branches of machine learning have already been investigated in the field of LSCM, for example, Vanvuchelen et al. (2020) suggesting reinforcement learning for control tower to manage multi-SC collaborative planning. Machine learning could also be applied in web API services (Tan et al., 2016), that are becoming increasingly important in LSCM. However, data privacy and security still remain an issue. The new branch, namely federated learning could be an effective way to address the issue. First promoted by Google AI in 2017, federated learning is defined as "*collaborative machine learning without centralized training data*[1]". Relying on consensual learning protocols and distributed learning methods, the mechanism defines that parties do not need to consolidate their data to a central authority (orchestrator or data platform), because algorithms will directly learn from the local data and only communicate the processed and aggregated information (e.g., gradient) to the central algorithm for global optimization, according to (Yang et al. 2019). Furthermore, recent research proposes to combine federated learning and differential privacy methods to improve the performance (Rodríguez-Barroso et al., 2020). Generally, federated learning can be applied to different types of distributed and decentralized data sources, such as IoT devices, company databases, clouds. Thanks to the data privacy-preserving mechanism, its potential to federated logistics networks (like PI) should be tremendous. But until now no sufficient attention has been paid to this avenue.

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[1] https://ai.googleblog.com/2017/04/federated-learning-collaborative.html

On the practical side, GS1 is a recognized organization for logistics data standards, such as RFID, EPCIS, and SSCC standards. Beyond those of GS1, there exists many other standards at operational level. How to connect these standards, and what is the impact on logistics performance, are questions still needing to be investigated. Regarding data communications, using an API or a central data platform are the widespread conventional approaches. Some recent or undergoing projects can be cited here for a best-practices survey. For example, Clusters 2.0 (clusters20.eu), DataPorts (dataports-project.eu), FENIX (fenix-network.eu), and LOGISTAR (logistar-project.eu), in Europe, Freight Share Lab (freightsharelab.com) in UK, and Cainiao Network in China. Furthermore, the graph paradigm is an approach increasingly used for managing and connecting databases, for example the graph database management systems like *Amazon Neptune*, *Microsoft Graph*, and *Neo4j* (Angles, 2018).

5.2 Autonomous and self-organizing logistics systems

The second approach concerns autonomous and self-organizing logistics systems, that are the logistics systems that can function and automate processes (including self-decision-making and self-executing) without significant outside intervention (Bartholdi III et al., 2010; Pan et al., 2017b). This is a relatively new research trend in the field, often for the purpose of designing more agile, efficient and cost-effective logistics systems (Lee et al., 2015). The key technologies for communication in such systems are, for example, IoT standards such as web of things, or M2M communication with the support of adequate ICT technologies like 5G, Lora, etc. (standards discussed in (Garcia et al., 2018; Sneps-Sneppe and Namiot, 2012)). Regarding product-oriented and order-oriented data interoperability, IoT or AI-enabled intelligent (or smart) products are becoming an essential research avenue. The new edge computing technology, which aims at processing information and making decision locally at data sources' or consumers' level, is also expected to contribute significantly. Especially, autonomous and self-organizing logistics systems are attracting increasing attention in the field of city logistics. Autonomous transportation systems are the most studied topic in research and in industrial development, including intelligent transportation system (ITS), autonomous vehicles (e.g. delivery droid), last-mile delivery drones (e.g. UPS, Amazon), or autonomous underground freight transportation systems (e.g. Swiss Cargo). Moreover, there are also autonomous systems for other logistics activities like autonomous warehousing and picking (e.g. Autostore), automated guided vehicles (AGV) or robot in sorting centers (e.g. Kiva). Most of these autonomous systems are designed to improve the efficiency of the logistics service offered by one service provider (transportation, warehousing, etc.). One of the next challenges will be the interconnection of such systems to offer integrated end-to-end logistics services, via ensuring the tracking of responsibility and error, at global, inter-city or city level of logistics. Multi-agent systems is one of the promising approaches for investigating such challenges.

Blockchain and Smart Contracts shape research opportunities worth particularly mentioning for this approach (Wang et al., 2019). Blockchain technology is showing good potential in connecting data(bases), because of its distinguishing advantage in handling data privacy and security, and responsibility tracking (Hofmann and Rüsch, 2017). It is foreseeable that smart contract technology that can automate agreement-based processes will further promote the application of blockchain in autonomous and self-organizing logistics systems and enhance the added value (Betti et al., 2020, 2019; Christidis and Devetsikiotis, 2016). According to Wang et al. (2019), smart contracts will prevail in supply chain collaborations and ecosystems, as a result of their particular advantage for decentralized collaboration. Wang et al. (2021) has already investigated its potential in circular SCM in fashion industry, for end-to-end traceability and visibility. We also believe that this research avenue will be a disruptive way to enhance data interoperability. For example, large technology companies start to provide Blockchain-as-a-service solutions, such as IBM Hyperledger Fabric platform as part of the Hyperledger project for open source blockchains. These solutions are attracting growing attention from the logistics sector for digitalization and interoperability, see the platform Tradelens (tradelens.com) for example.

5.3 Digital Twins in Logistics and Supply Chain

Aligned with Industry 4.0, the Digital Twin (DT) concept, widely used in manufacturing and production research, aims at representing a physical object by an online digital representation for data-driven optimization, *as per* the definition suggested by Tao et al. (2018). Recently, its application has extended to LSCM. The terms *Digital Supply Chain Twin* (DSCT) and *Logistics Digital Twin (LDT)* have appeared in several works, with the goal of improving the performance of SC and logistics. For example, Ivanov and Dolgui (2020b) suggest a framework of DSCT for data-driven SC disruption management. These research works also prove that DT could significantly contribute to digital interoperability in PI, especially in meeting the challenge of product-oriented and order-oriented data, e.g., life cycle assessment

(Lim et al., 2020), maintenance (Errandonea et al., 2020), BIM in construction industry (Greif et al., 2020). Practical examples can be found in some projects such as *DISpATch* (dispatch-project.be) in Belgium, the EU project LEAD (leadproject.eu), or the IoT platform *Thing'in* (tech.thinginthefuture.com) by Orange in France.

The information and communication technologies for DSCT are similar to those for autonomous systems as depicted above, but requiring more effort on virtual-physical communication and real-time data processing. To this end, new standardization technologies, such as semantics (*viz.* web application framework for machine-readability) and ontology (*viz.* open vocabularies to describe area of interest), are attracting particular attention in the DT related research streams (Grubic and Fan, 2010). The technologies of cloud and fog computing are also being investigated for using on-demand computational capacity for real-time data processing, which is critical for connecting the digital and physical worlds (Borangiu et al., 2019). It is very likely that more research will be devoted to these technologies and their applications in DSCT. Regarding data privacy and security in interoperability, in addition to the emerging technologies discussed above, sensors and cloud security seem the common conventional solutions to this end. This brings a call for more research attention.

5.4 Smart infrastructures and communities

The approach of smart infrastructures and communities is concerned with data interoperability between logistics entities (assets, parties, etc.) and the smart environment (infrastructures, communities, ecosystems, etc., that are supporting or impacted by logistics activities). This approach becomes increasingly important because of, on the one hand, the fast development of smart infrastructures and, on the other hand, the requirement of sustainable SC and logistics. Smart city is a good example to illustrate its importance. Under the paradigm, it can be assumed that logistics operations would perform better thanks to real-time infrastructure data and information such as GIS or traffic data, see the case in (Kong et al. 2020) for example. The data exchange and interoperability between logistics entities and infrastructures is essential for dynamic, efficient planning, e.g., V2I (Vehicle-to-Infrastructure) communication. Besides, it is also important to consider actual logistics constraints from infrastructures or communities, to explore the possible and mutual synergies of inhabitant mobility and freight transportation for one thing, and to reduce the negative externalities from logistics for another (Crainic and Montreuil, 2016). Direct and real-time access to the data and information sources (e.g. local regulations, urban accessibility) is the key step.

Some enabling technologies and concepts are arising. For example, real-time data marketplaces can be implemented to pool data from different sources (organizations, devices, systems…) for exchanging and for endowing new values. Different from data platforms, data marketplaces are more open to stakeholders in ecosystems (Ramachandran et al., 2018). Logistics entities may directly access to data through such marketplaces. Another emerging technology of interest is context awareness technology, that is widely studied in ubiquitous computing (El Kadiri et al., 2016), but less for LSCM. In coupling with the aforementioned autonomous and self-organizing logistics systems, they will contribute toward making SC and logistics more effective, efficient, agile, and resilient. Regarding privacy and security issues, the aforementioned technologies are applicable in this approach as well, but must consider all stakeholders in the ecosystems.

6. Conclusion

This paper investigated digital interoperability in logistics and supply chain management (LSCM), with particular reference to Physical Internet (PI) paradigm. We first conducted a bibliometric analysis to track the critical topics and trends, based on a dataset of 208 papers from the related literature. The statistical results reveal that the issue of digital interoperability in LSCM has been deeply studied in the past decade, and a number of solutions and concepts have been developed. However, there appears to be a lack of structural classification to bridge the gap between the state-of-the-art solutions and PI because of its novelty. Therefore, we suggested four most important interoperability challenges induced by the PI paradigm, which served as a framework to classify the solutions. The results show that the present state-of-the-art solutions of digital interoperability are not fully aligned with PI requirements, and this brings new research perspectives. Then, future interdisciplinary research approaches and avenues are outlined for the goal of achieving digital interoperability in the PI.

Several conclusions can be drawn from the work. First, the innovative program PI reinforces and extends emphasis on digital interoperability issues, such as data sharing, communications, and data privacy preservation. Second, PI introduces new requirement of data interoperability such as product-oriented and order-oriented data, in which cross organizational data threads require seamless management. Third, interdisciplinary approaches and solutions provide promising research perspectives for digital interoperability in PI.

The paper contributes to the related literature as it has highlighted important research gaps and opportunities in the logistics and supply chain fields, via contributing simultaneously to the literature on interoperability and on the PI. On the practical side, emerging ICT solutions are categorized and mapped relative to the avenues according to their potentiality. The paper also identifies a toolbox of solutions deemed most appropriate, guiding practitioners in selecting technologies for contributing to the PI development and to leverage its growing availability.

As a limitation, this work investigated only peer-reviewed scientific publications so that contributions as well as requirements from practitioners might be insufficiently addressed. To better bridge the gap between academic research and industrial R&D, this paper encourages further research to study the so-called grey literature (for example, relevant government documents, company's reports, whitepapers, patents related to digital interoperability), which is complementary to scientific publications. Such a research would also help further investigate the practicability and feasibility of the suggested research avenues and approaches, via considering the practical requirements from the fields of application.

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